Darcy-Weisbach Roughness Coefficients for Gravel and Cobble Surfaces

By John E. Gilley,[1] Eugene R. Kottwitz,[2] and Gary A. Wieman[3]

Abstract: A laboratory study is conducted to measure Darcy-Weisbach roughness coefficients for selected gravel and cobble materials. Varying rates of flow are introduced into a flume in which a given size class of gravel or cobble material is securely attached. Roughness coefficients are calculated from measurements of discharge rate and flow velocity. The laboratory data are used to develop regression equations for relating roughness coefficients to surface cover and Reynolds number. The regression relations, which are developed for values of the Reynolds number from approximately 500 to 16,000, are tested using hydraulic data collected on surfaces containing a distribution of size classes. Close agreement between predicted and measured Darcy-Weisbach roughness coefficients is obtained by adding the roughness contributions of individual size classes. Equations are also presented for estimating surface cover from measurements of gravel and cobble mass. Accurate prediction of roughness coefficients for gravel and cobble surfaces will improve our ability to understand and properly model upland flow hydraulics.

Introduction

Calculation of time of concentration, determination of flow velocity, and simulation of runoff hydrographs require the use of roughness coefficients. Resistance to flow on upland areas may be influenced by soil microrelief, standing vegetative material, residue cover, surface rocks, raindrop impact, and other factors. Roughness coefficients caused by each of these components contribute to total hydraulic resistance. In this study, Darcy-Weisbach roughness coefficients were identified for gravel and cobble surfaces.

Recommendations for estimating friction factors in open channels were made by an ASCE task force ("Friction" 1963). A review of the development of fixed-bed, open-channel resistance formulas was provided. In addition, a comprehensive bibliography and suggested research topics were presented.

A description of previous studies involving roughness coefficients on agricultural areas was provided by Engman (1986). Hydraulic roughness coefficients were developed from runoff plot data originally collected for erosion studies. Friction factors were presented in a tabular format with a description of various surfaces and land uses.

Liong et al. (1989) developed a simple method for assigning roughness coefficients to overland flow segments in kinematic wave models. The proposed method was found to work well on a gauged basin. This procedure may be useful in estimating hydrographs for ungauged watersheds.

Hydraulic characteristics of rills were measured by Gilley et al. (1990) on

[1]Agric. Engr., U.S. Dept. of Agric.–Agric. Res. Service, 251 Chase Hall, University of Nebraska, Lincoln, NE 68583-0729.

[2]Res. Engr., Dept. of Biological Systems Engrg., 248 Chase Hall, Univ. of Nebraska, Lincoln, NE 68583-0729.

[3]Res. Engr., Dept. of Biological Systems Engrg., 229 Chase Hall, Univ. of Nebraska, Lincoln, NE.

Note. Discussion open until July 1, 1992. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on November 12, 1990. This paper is part of the ***Journal of Irrigation and Drainage Engineering***, Vol. 118, No. 1, January/February, 1992. ©ASCE, ISSN 0733-9437/92/0001-0104/$1.00 + $.15 per page. Paper No. 889.

several sites located throughout the United States. Regression equations were developed that related roughness coefficients to the Reynolds number. A laboratory study was also performed by Gilley et al. (1991) to measure roughness coefficients for selected residue materials. The laboratory data were used to derive regression equations for estimating roughness coefficients based on residue cover and the Reynolds number.

Laboratory measurements of roughness coefficients on surfaces covered with sand or gravel were made by Woo and Brater (1961), Emmett (1970), Phelps (1975), and Savat (1980). Similar tests were performed under field conditions on natural landscapes by Dunne and Dietrich (1980), Roels (1984), and Abrahams et al. (1986). In most of these studies, roughness coefficients decreased with increasing Reynolds number. Once roughness elements were submerged, their ability to retard overland flow was reduced as the depth of overland flow became greater. The objective of this investigation was to develop regression equations for estimating Darcy-Weisbach roughness coefficients for gravel and cobble surfaces.

Hydraulic Equations

The Darcy-Weisbach equation has been widely used to describe flow characteristics. Under uniform flow conditions, the Darcy-Weisbach roughness coefficient, f, is given as (Chow 1959)

$$f = \frac{8gRS}{V^2} \qquad (1)$$

where g = acceleration due to gravity; S = average slope; V = flow velocity; and R = hydraulic radius, defined as

$$R = \frac{A}{P} \qquad (2)$$

where A = cross-sectional flow area; and P = wetted perimeter. For a rectangular flume with width w

$$R = \frac{wy}{w + 2y} \qquad (3)$$

where y = flow depth. For overland flow conditions where flow width is much greater than flow depth, hydraulic radius can be assumed to be approximately equal to flow depth.

The Reynolds number, R, is also used to describe flow characteristics, and is given as

$$\mathsf{R} = \frac{VR}{\nu} \qquad (4)$$

where ν = kinematic viscosity. Kinematic viscosity can be determined directly from water temperature.

The continuity equation for flow is defined as

$$Q = VA \qquad (5)$$

where Q = flow rate. For a rectangular flume, water depth is given as

$$y = \frac{Q}{Vw} \qquad (6)$$

In this study, water depth was determined indirectly using (6) and measurements of Q, V, and w.

Experimental Procedures

The size classes of gravel and cobble materials used in this study are shown in Table 1. The material varying in size from 0.25 to 12.70 cm was removed from a rangeland site near Tombstone, Arizona. Cobble material with a diameter of 12.70–25.40 cm, which was obtained near Lincoln, Nebraska, was also used in the laboratory tests.

Shape factors (Guy 1969) for each of the size classes are shown in Table 1. Shape factors provide a relative estimate of the physical configuration of gravel and cobble material. Little variation in shape factor was found between size classes. For natural sediments, which are usually much smaller, a shape factor of 0.7 is typical (Guy 1969).

Gravel and cobble materials were glued in a random orientation onto a section of reinforced fiberglass sheeting located within a flume. Surface-cover values for each of the size classes are shown in Table 1. The percentage of surface cover was measured using a photographic grid procedure (Laflen et al. 1978). Gravel and cobble materials on the fiberglass sheets were photographed using 35-mm color slide film. The slides were projected onto a screen on which a grid had been superimposed. The number of grid intersections over gravel and cobble material was determined visually from the projected slides and surface cover was then calculated.

The 0.91-m-wide, 7.31-m-long, 0.279-m-deep flume was maintained at a slope of 1.35%. Water was supplied to the flume using a constant head tank. Two replicate tests were run at 10 flow rates ranging from approximately 4.23×10^{-4} to 1.35×10^{-2} m^3/s. Flow rate was determined immediately before and after each test to ensure steady-state conditions. Water temperature was measured following flow rate determinations.

Reynolds numbers varied from approximately 500 to 16,000. Maintaining uniform flow conditions on the gravel- and cobble-covered surfaces was difficult for Reynolds numbers less than approximately 500. For Reynolds numbers greater than 16,000, little variation in roughness coefficient values was found.

Once steady-state runoff conditions had become established, line sources

TABLE 1. Surface Cover and Shape Factors for Selected Size Classes of Gravel and Cobble Material

Diameter (cm) (1)	Surface cover (%) (2)	Shape factor[a] (3)
0.25– 1.27	6, 15, 37, 66, 90	0.51
1.27– 2.54	7, 13, 32, 61, 90	0.52
2.54– 3.81	4, 16, 32, 56, 80	0.49
3.81–12.70	6, 17, 33, 61, 89	0.47
12.70–25.40	9, 13, 24, 61, 83	0.52

[a]Shape factor, SF, is given as (Guy 1969) SF = $c/(ab)^{1/2}$, where a = longest axis, b = intermediate axis, and c = shortest axis.

of fluorescent dye were injected across the flume at downslope distances of 0.91 and 7.01 m. A fluorometer and a stopwatch were used to determine elapsed travel time between the dye concentration peaks. Mean flow velocity was calculated by dividing the distance between the two line sources of dye (6.10 m) by the difference in travel time between the two dye concentration peaks. For each test sequence, three measurements of flow velocity were made.

Roughness coefficients for the fiberglass sheets that supported the gravel and cobble materials were also identified. The experimental procedures used to measure roughness coefficients for the fiberglass sheets with and without gravel and cobble material were identical. Roughness coefficients induced by the bare fiberglass sheets at a given Reynolds number were subtracted from measurements obtained with gravel and cobble material to determine hydraulic resistance caused by the gravel and cobble material alone.

Tests were also run using three distributions of size classes. The percentages of cover in each size class for each distribution are shown in Table 2. These tests were conducted to estimate total hydraulic roughness from equations developed for individual size classes.

The mass of gravel or cobble material required to provide a given surface cover was measured. Surface covers of approximately 5%, 15%, 35%, 50%, 65%, 80%, and 95% were used for each of the five size classes. Gravel or cobble material was placed on a 0.581-m^2 area until the approximate desired surface cover was obtained. Actual cover was identified using a photographic grid procedure (Laflen et al. 1978). The gravel or cobble material was then removed and its mass determined. Two replicate tests were performed for each surface cover.

RESULTS

Darcy-Weisbach roughness coefficients at varying Reynolds numbers for gravel material with a diameter of 2.54–3.81 cm are shown in Fig. 1. The trends presented in Fig. 1 are characteristic of gravel and cobble materials having diameters ranging from 0.25 to 12.70 cm.

For the experimental runs shown in Fig. 1 with surface covers of 56% and 80%, water depth was usually greater than the height of the gravel material. As a result, Darcy-Weisbach roughness coefficients consistently decreased as the Reynolds number became larger. In contrast, water depths at lower Reynolds numbers for the test runs with surface cover values of

TABLE 2. Percent Cover Provided by Selected Size Classes Used in Validation Test Series

Diameter (cm) (1)	Percent Cover in Test Series 1 (2)	2 (3)	3 (4)
0.25– 1.27	21	3	16
1.27– 2.54	31	11	9
2.54– 3.81	14	18	38
3.81–12.70	13	28	11
12.70–25.40	9	30	15
Total cover	88	90	89

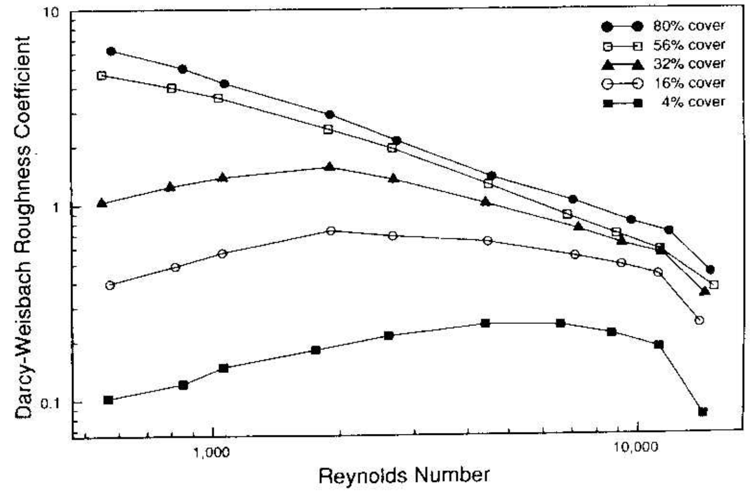

FIG. 1. Darcy-Weisbach Roughness Coefficients versus Reynolds Number for Gravel Material with 2.54–3.81-cm Diameter

4%, 16%, and 32% were typically less than the height of the gravel material. As a result, roughness coefficients initially increased with the Reynolds number. Once flow depth exceeded roughness element height, roughness coefficients became smaller as the Reynolds number increased.

Water depths were usually smaller than the height of the roughness elements for the cobble material having a diameter of 12.70–25.40 cm. As a result, Darcy-Weisbach roughness coefficients generally increased with the Reynolds number (Fig. 2). However, the surfaces with 61% and 83% cover showed a substantial reduction in roughness coefficient values at the highest Reynolds number. For this hydraulic condition, flow depth exceeded the height of many of the roughness elements.

Regression equations that relate Darcy-Weisbach roughness coefficients to percent cover and Reynolds number are shown in Table 3. Regression relations are presented for the five selected size classes. In addition, data for gravel and cobble materials having a diameter range of 0.25–12.70 cm were combined to obtain a generalized regression equation.

TESTING OF REGRESSION EQUATIONS FOR MULTIPLE SIZE CLASSES

Laboratory data collected on the surfaces described in Table 2 that contained multiple size classes were used to test the reliability of the regression equations. Darcy-Weisbach roughness coefficients were first calculated for each size class using the equations shown in Table 3. Roughness contributions for each of the five size classes were then added to find the total roughness for the given surface. Darcy-Weisbach roughness coefficients were determined for each Reynolds number value used in the laboratory tests.

Predicted versus measured Darcy-Weisbach roughness coefficients are presented in Fig. 3. Close agreement between predicted and measured values was found for each test series. Linear regression analysis of predicted

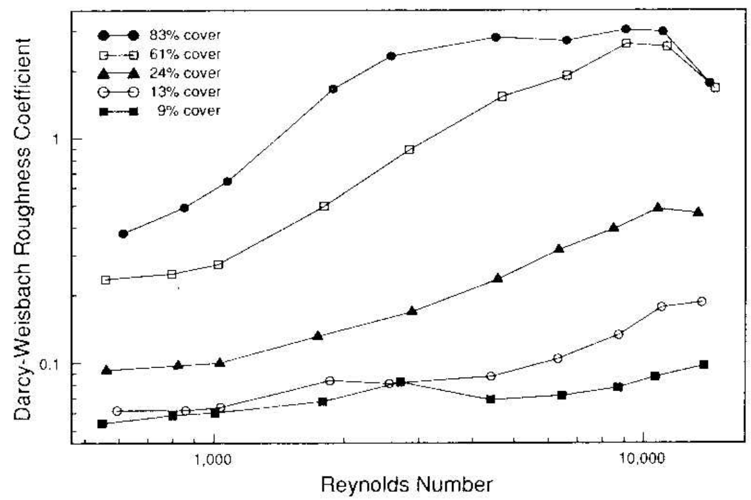

FIG. 2. Darcy-Weisbach Roughness Coefficients versus Reynolds Number for Cobble Material with 12.70–25.40-cm Diameter

TABLE 3. Regression Equations Relating Darcy-Weisbach Roughness Coefficient to Percent Cover and Reynolds Number for Selected Size Classes

Diameter (cm) (1)	Regression Coefficients[a] h (2)	Regression Coefficients[a] i (3)	Regression Coefficients[a] j (4)	Coefficient of determination, r^2 (5)
0.25– 1.27	1.68×10^1	5.78×10^{-1}	7.09×10^{-1}	0.985
1.27– 2.54	1.18×10^1	6.78×10^{-1}	6.67×10^{-1}	0.945
2.54– 3.81	1.91	1.19	6.28×10^{-1}	0.943
3.81–12.70	1.11×10^{-1}	1.61	4.68×10^{-1}	0.944
12.70–25.40	1.25×10^{-5}	1.63	-5.68×10^{-1}	0.944
0.25–12.70[b]	2.16	9.53×10^{-1}	5.50×10^{-1}	0.672

[a]Regression coefficients h, i, and j are used in: $f = h(\text{percent cover})^i/R^j$.

[b]Data for gravel and cobble materials having a diameter range of 0.25–12.70 cm were combined to obtain a generalized regression equation.

versus measured roughness coefficients yielded a coefficient of determination, r^2, value of 0.983. Thus, it appears that reliable estimates of Darcy-Weisbach roughness coefficients can be obtained by adding the roughness contributions of individual size classes.

ESTIMATING GRAVEL AND COBBLE COVER

The regression equations identified in Table 3 require an estimate of the percentage of cover provided by gravel or cobble material in a given size class. Information concerning the amount of ground cover on surfaces with a distribution in size of gravel and cobble materials is limited. Data on the

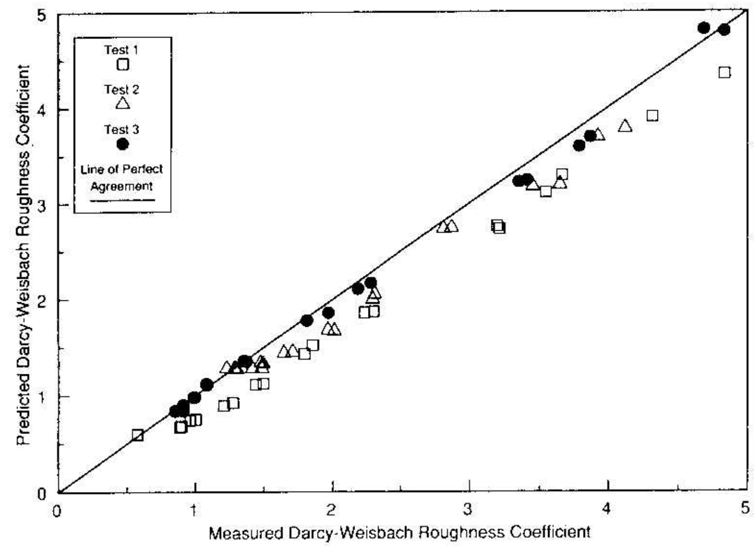

FIG. 3. Predicted versus Measured Darcy-Weisbach Roughness Coefficients

TABLE 4. Regression Equations Relating Percent Cover to Gravel or Cobble Mass for Selected Size Classes

Diameter (cm) (1)	Regression Coefficients[a] k (2)	Regression Coefficients[a] l (3)	Coefficient of determination, r^2 (4)
0.25– 1.27	1.78×10^1	7.39×10^{-1}	0.964
1.27– 2.54	6.60	9.35×10^{-1}	0.974
2.54– 3.81	3.09	1.01	0.997
3.81–12.70	2.66	8.96×10^{-1}	0.997
12.70–25.40	4.90×10^{-1}	1.02	0.987

[a]Regression coefficients k and l are used in: percent cover $= k(\text{gravel or cobble mass}/A)^l$, where surface cover is given as a percentage, gravel or cobble mass is in kilograms, and B is the area in square meters from which the gravel or cobble material was obtained.

size distribution of material obtained on the basis of mass may be more readily available and easier to obtain.

To acquire size-distribution data, surface material from a given area is removed and run through a series of nested sieves. When collecting material from the field, only the gravel and cobble material on the surface should be removed. By dividing the mass of the material on a given sieve by the total mass of the sample, the percentage of material in a given size class can be identified.

Experimental measurements of the mass of gravel or cobble material corresponding to a given surface cover were used to develop the regression equations shown in Table 4. Gravel and cobble materials vary widely in geologic origin, and may therefore have different physical characteristics.

Predicting percent cover from measurements of gravel or cobble mass worked well for the materials used in this study. However, it may be necessary to derive separate relationships for other gravel and cobble materials.

Summary and Conclusions

Hydraulic roughness coefficients are required to analyze surface runoff on upland areas. Total hydraulic resistance on a site is usually caused by several factors. Roughness coefficients for gravel and cobble materials were examined in this investigation.

Gravel or cobble diameter, percent surface cover, and flow rate were the experimental variables used in this study. Gravel or cobble material of a given size class was glued in a random orientation onto fiberglass sheets that had been placed in a flume. Steady uniform flow conditions were then established at several discharge rates.

Flow measurements were used to calculate Darcy-Weisbach roughness coefficients. Regression relationships were developed for relating roughness coefficients to percentage of surface cover and the Reynolds number. The regression equations can be used for values of the Reynolds number from 500 to 16,000.

Laboratory tests were also conducted to measure roughness coefficients for surfaces containing multiple size classes. These data were used to test the accuracy of the previously identified regression relationships. Reliable estimates of Darcy-Weisbach roughness coefficients were obtained by adding the roughness contributions of individual size classes.

Information on the size distribution of surface material obtained on the basis of mass may be more readily available and easier to obtain. In this study, measurements were made of the mass of gravel or cobble material corresponding to a given surface cover. These data were used to develop regression equations for relating surface cover for a given size class to gravel or cobble mass.

Total hydraulic resistance on upland areas may be caused by several factors. Information is needed on roughness coefficients provided by each of these factors, their contribution to total hydraulic roughness, and the effect of flow rate on roughness coefficients. Our ability to understand and accurately model upland flow hydraulics will improve as this information becomes available.

Acknowledgments

This paper, journal series No. 9420, is a contribution from the U.S. Department of Agriculture–Agricultural Research Service, Lincoln, Nebraska, in cooperation with the Agricultural Research Division, University of Nebraska, also in Lincoln.

Appendix I. References

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Appendix II. Notation

The following symbols are used in this paper:

A = cross-sectional flow area;
a = longest axis of gravel or cobble material;
B = area from which gravel or cobble material was obtained;
b = intermediate axis of gravel or cobble material;
c = shortest axis of gravel or cobble material;
f = Darcy-Weisbach roughness coefficient;
g = acceleration due to gravity;
h, i, j, k, l = regression coefficients;
P = wetted perimeter;
Q = flow rate;
R = hydraulic radius;
R = Reynolds number;
S = average slope;
SF = shape factor;
V = flow velocity;
w = flow width;
y = flow depth; and
ν = kinematic viscosity.